Batteries Included:

Top 10 Findings from Berkeley Lab Research on the Growth of Hybrid Power Plants in the United States

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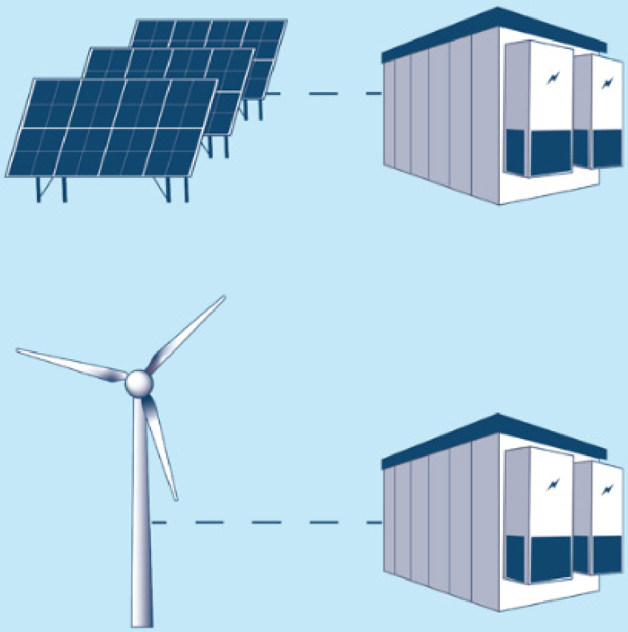
One of the most important electric power system trends of the 2010s was the rapid deployment of wind turbines and photovoltaic arrays, but early data suggests a twist for the 2020s may be the rapid deployment of 'hybrid' generation resources. Hybrid power plants typically combine solar or wind (or other energy sources) with co-located storage. Just as cost declines drove last decade's wind and solar expansion, falling battery prices and growing needs to integrate variable renewable energy generation are driving plans to deploy hybrid power plants. While hybridization helps to ease the challenge of balancing variable supply and demand, its relative novelty means that research is needed to facilitate integration and promote innovation.

Combining the characteristics of multiple energy, storage, and conversion technologies poses complex questions for grid operations and economics. Project developers, system operators, planners, and regulators would benefit from better data, methods, and tools to estimate the costs, values, and system impacts of hybrid projects. The opportunity for hybrids is clearly large as we move toward greater levels of renewable energy, but their implications and optimal applications have yet to be established.

This briefing showcases some of Berkeley Lab's robust research program intended to support private- and public-sector decision-making about hybrid plants in the United States. We analyze where and why hybrids are being built. We model optimal hybrid design choices and assess hybrid contributions to resource adequacy and short-term reliability. We evaluate how hybrids participate in wholesale power markets and investigate the cost and value of both customer-sited and utility-scale hybrids. Finally, we identify future research needs and questions.

How do we define hybrid power plants?

- Combinations of generation and battery storage
- Operated either as a single or two separate units
- Sited at the same location



The top ten findings

GROWTH

Developer interest in hybrid power plants is strong and growing

PRICE VS. VALUE

PV+storage hybrids have low PPA prices and high value in some regions

MARKET DRIVERS

Solar hybridization is driven by tax credits and other benefits

CONFIGURATION CHOICES

Market prices have incentivized shorter duration batteries with PV

CAPACITY VALUE

The capacity contribution of a hybrid is less than the sum of its parts

ANCILLARY SERVICES

Ancillary service markets are a valuable yet fleeting option for hybrids

MARKET PARTICIPATION

Hybrids can more flexibly engage with electricity markets

OPERATIONS

The power system value of hybrids depends on how they are operated

DISTRIBUTED HYBRIDS

Growth of customer-sited PV+storage hybrids offers new opportunities

FUTURE RESEARCH

Where next? Priority areas for hybrid power research

About the Authors

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Abbreviations

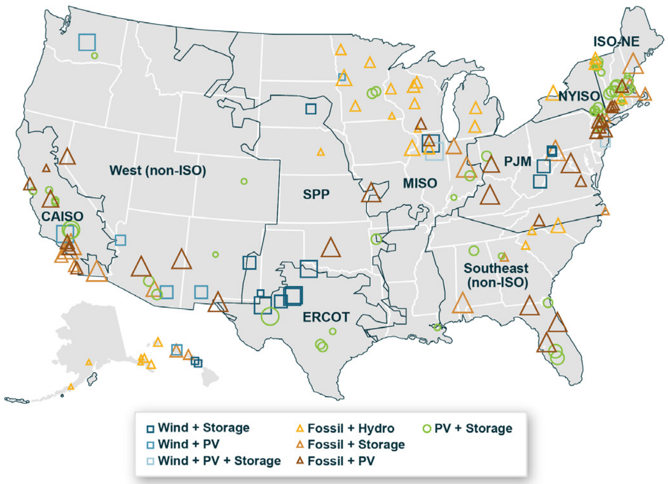
AS	Ancillary Services
CAISO	California Independent System Operator
BTM	Behind The Meter
DOE	U.S. Department of Energy
ELCC	Effective Load Carrying Capacity
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
ITC	Investment Tax Credit
ISO	Independent System Operator
ISO-NE	ISO New England
MISO	Midcontinent Independent System Operator
NYISO	New York Independent System Operator
PJM	PJM Interconnection
PPA	Power Purchase Agreement
PV	Photovoltaic
RTO	Regional Transmission Organization
SPP	Southwest Power Pool

GROWTH

Developer interest in hybrid power plants is strong and growing

Falling battery prices and the growth of variable renewable generation are driving a surge of interest in hybrid power plants (generating capacity with co-located storage). Current interest is mostly directed toward pairing solar photovoltaic (PV) plants with batteries, but a wide range of generator and storage pairings is possible.

FIGURE 1. Location of Existing Hybrid Plants Through 2020



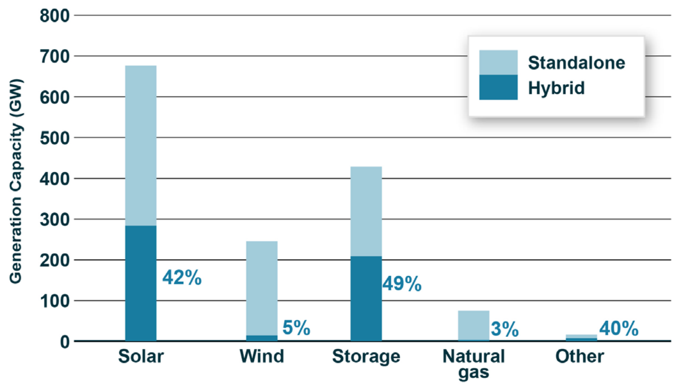
By the end of 2021, there were more than 8 GW of PV or wind hybrid plants online

PV hybrids dominate this total, representing over 5.9 GW of hybrid capacity, compared to only 2 GW of wind hybrids and 750 MW of PV+wind+storage hybrids. This market has started to achieve exponential growth, with cumulative operational hybrid capacity increasing by 133% in 2021 compared to the online capacity at the end of 2020. Though there are a number of fossil+storage hybrid projects, they include a relatively low amount of storage compared with the size of the generation plant.

Proposed plants indicate growing interest in renewable hybrid configurations

Data on plants under development from the interconnection queues of all seven organized wholesale markets plus 35 utilities demonstrate considerable commercial interest in hybrid plants (Figure 2). At the close of 2021, there were more than 675 GW of solar plants in the nation's queues; 286 GW (~42%) of this capacity was proposed as a hybrid, most typically pairing PV with storage. For wind, 247 GW of capacity sat in the queues, with 19 GW (~8%) proposed as a hybrid, again most often pairing wind with storage. While many of these proposed plants will ultimately not reach commercial operations, the depth of interest in hybrid plants portends strong growth. This is especially true in the California Independent System Operator (CAISO) region, where 95% of all solar capacity and 42% of all wind capacity in the queue was proposed as hybrid plants.

FIGURE 2. Capacity in Queues Through 2021



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PRICE VS. VALUE

PV+storage hybrids have low PPA prices and high value in some regions

Though the number of operational hybrid plants is still small (but growing), we can gain insight into upcoming hybrid plant configurations and pricing by reviewing power purchase agreements (PPAs), which are often executed several years before a plant becomes operational. Berkeley Lab's analysis of an extensive sample of hybrid (and standalone) PV plant PPAs, in conjunction with value modeling of similar hybrid plant configurations, helps to explain the growing appeal of PV hybrids in some regions.

The price of PV hybrid plants is low, and falling

Within Berkeley Lab's utility-scale PPA price sample, the per-MWh price of PV hybrids (shown in Figure 3 by open circles that are sized to reflect the battery-to-PV capacity ratio) is close to that of standalone PV plants (smaller filled circles, not sized). As a result, PV hybrids have become increasingly common over time. In Hawaii (orange), virtually all utility-scale PV plants with PPAs executed post-2017 include a battery, and the balance seems to be shifting among the other four states shown (in blue). These levelized PPA prices reflect the receipt of the federal investment tax credit (ITC).

A hybrid's PPA price premium reflects the size of its battery

A sub-sample of 17 PPAs separate the pricing of the PV and storage components, enabling us to calculate exactly how much storage adds to the PPA price. This "levelized storage price adder" increases linearly with the battery-to-PV capacity ratio (Figure 4), and is one of several reasons why Hawaiian hybrids—all with relatively larger batteries—are priced at a premium over the other states in Figure 3.

The net value of hybridization appears to be positive

To see whether the PPA price adder shown in Figure 4 is worth it, we modeled the value of adding 4-hour batteries sized at 50% of PV capacity to a standalone PV plant in both CAISO and ERCOT (Figure 5). Figure 4 suggests that this configuration should add $8-$13/MWh to PPA prices—comparable to the $11-$13/MWh value boost in the "low" case (simple dispatch based on day-ahead prices and generation profiles), and well below the $21-$22/MWh "high" case (perfect foresight), shown in Figure 5. Of course, the value of hybridization will vary over the life of the PPA, but—at least in recent years, and with the help of the ITC—the incremental value added appears to justify the price premium.

FIGURE 3. Levelized PV Hybrid PPA Prices by Execution Date

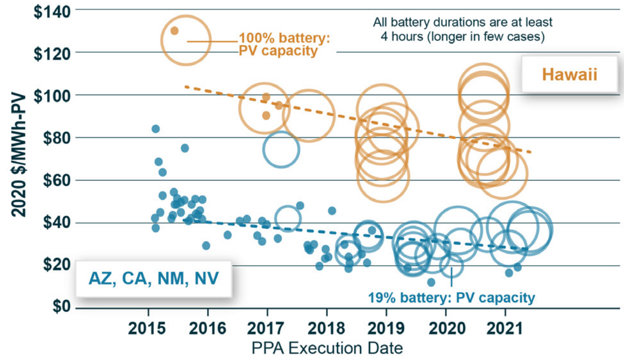


FIGURE 4. Levelized Storage PPA Price Adder by Capacity Ratio

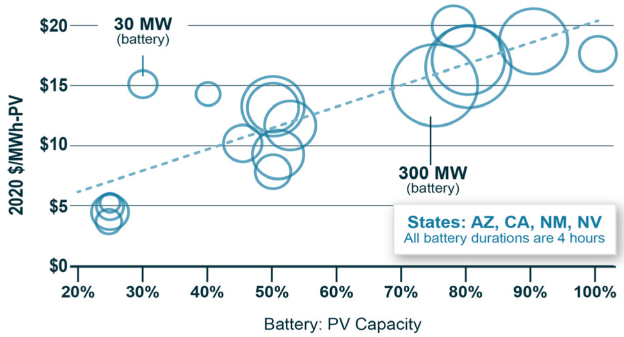
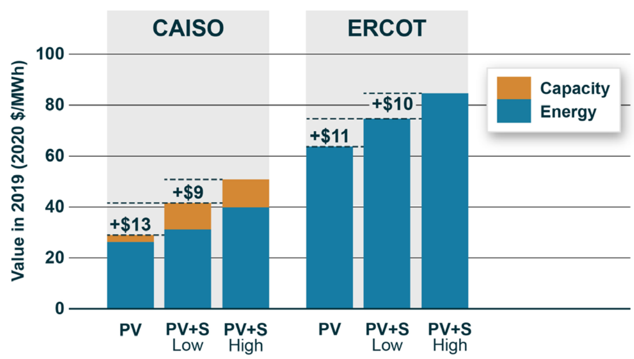


FIGURE 5. 2019 Market Value of Standalone PV and PV+storage Hybrids



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MARKET DRIVERS

Solar hybridization is driven by tax credits and other benefits

Hybrid plants with co-located renewable generators and batteries can benefit from tax credits, construction cost savings, and more flexible generator dispatch, but suffer from siting constraints. Berkeley Lab quantified the benefits and costs of hybridization and found a rough equivalence in their values, suggesting that the co-location choice is sensitive to local market conditions and configuration choices.

Tax Credits are one, but not the only, reason for hybridization

Co-locating PV and batteries can make the batteries eligible for the federal investment tax credit for solar, save on shared equipment and interconnection and permitting costs, capture otherwise clipped energy, and facilitate intraday energy shifting. Furthermore, variable generators paired with batteries have greater dispatch flexibility, making them more attractive for grid operations.

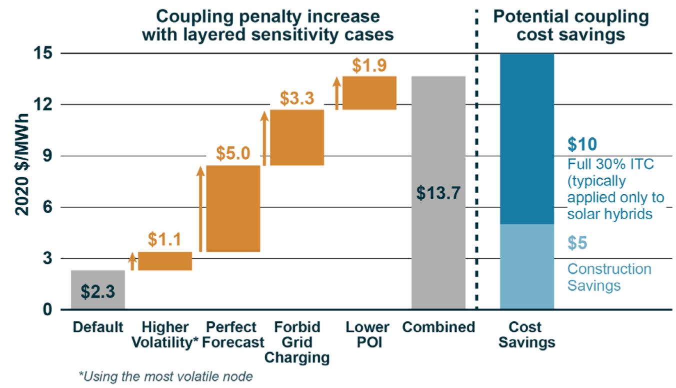
But a renewable project's location might not be where storage provides the most grid benefits

Large wind and solar projects are located where the resource is strong, land is available, and grid connections are possible. Alternatively, batteries can be put practically anywhere, like in high-value locations where they can provide additional values to the local grid, such as congestion relief and price volatility mitigation. We found that separately siting renewables and batteries results in \$2-\$9/MWh higher market value than co-location, depending on the region and year. This 'coupling penalty' averaged \$2/MWh across the seven organized wholesale markets (default case, Figure 6).

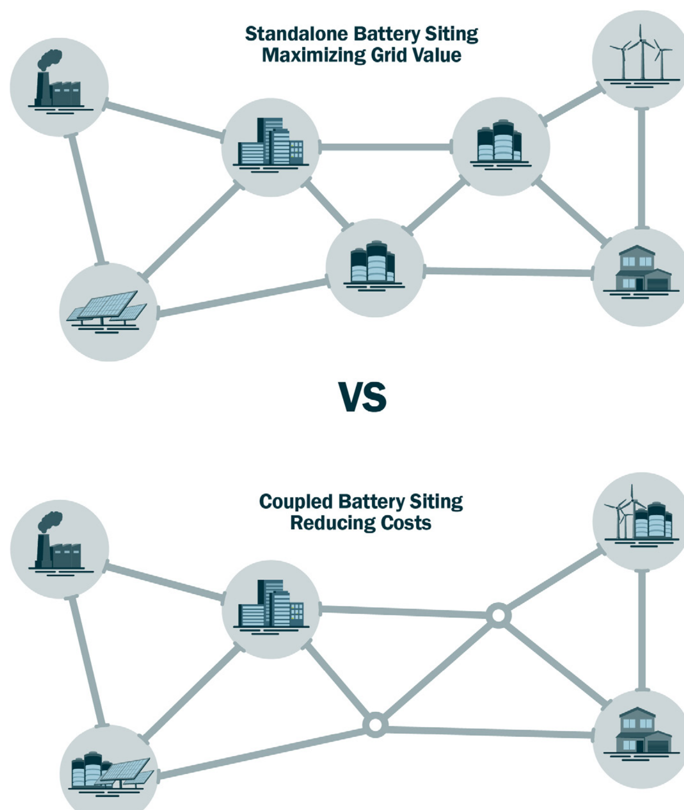
Higher standalone value is largely offset by hybrid cost savings

We calculated rough cost savings of \$15/MWh, with \$10 coming from the 30% ITC and \$5 from construction cost savings—both higher than the default coupling penalty. However, the coupling penalty can grow to \$14/MWh if batteries charge solely from the co-located renewable generator, if the interconnection capacity is limited to the generator's size, and if storage dispatch is operated with perfect foresight. Uncertainty in both the coupling penalty and cost savings from hybridization suggests both standalone and hybrid battery development models can be viable.

FIGURE 6. Averaged Coupling Penalty of Wind and Solar Generation with Storage under Various Scenarios



INFOGRAPH 1. Standalone vs Coupled Battery Siting



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Market prices have incentivized shorter duration batteries with PV

Berkeley Lab used wholesale market prices from 2012 to 2019 and a simple battery degradation model to compare the revenues and costs of different hybrid designs. We found significant variation by configuration and region with local solar penetration levels being a major factor. Hybrids were most attractive in CAISO and solar hybrids are more attractive than wind hybrids in most regions—trends that align with commercial activity.

Battery duration and capacity have the largest impact on hybrid net value

With the federal ITC, the most attractive hybrid configurations tend to have a two- to four-hour battery duration with batteries sized at either 25% or 100% of the solar or wind generator capacity, depending on the region (see Figure 7 for solar hybrids). Setting the grid interconnection capacity to allow simultaneous discharge of the generator and storage yields higher hybrid net values than limiting interconnection size to just the solar or wind generator power rating. Other configuration choices, such as the capacity of PV panels relative to the inverter capacity and the way that batteries and generators are coupled (before or after the inverter), have secondary impacts.

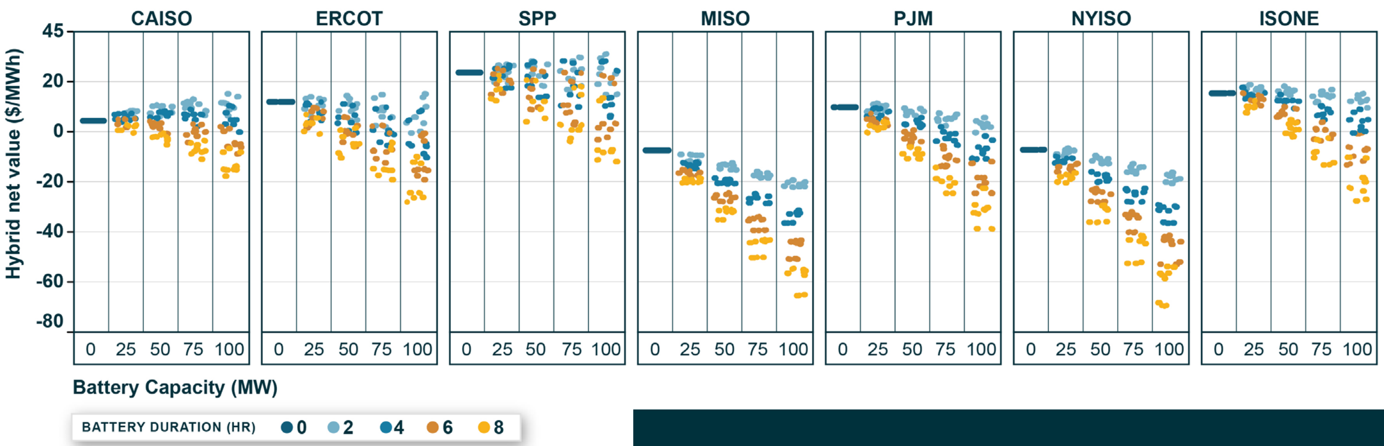
In CAISO, ERCOT, and SPP, net value is highest for solar hybrids with shorter duration batteries

Storage durations of online and proposed projects are typically 1-4 hours. Across all battery sizes, the relative value of hybrids was highest in CAISO, ERCOT, and SPP, locations with significant amounts of proposed solar hybrids. We also found that the net value of solar hybrids was comparatively more attractive than wind hybrids when incorporating the federal ITC, a trend seen commercially as well.

Region-wide solar penetration drives solar hybrid value

High solar penetrations shift the timing of peak grid prices from summer afternoons to evenings, and PV projects that can better align their production with this shifted "duck" profile will capture the most value. CAISO has so far seen the greatest impact, with an annual solar penetration level of 21% in 2020. However, PV project configurations that sacrifice generation to change the timing of production, such as west-facing arrays or vertical bifacial mounts, become redundant with the addition of storage's energy-shifting capabilities. Conversely, configurations that maximize PV generation—including via single-axis tracking and oversized PV arrays—provide the largest net-value gains when combined with storage.

FIGURE 7. Impact of Battery Power Capacity (x-axis) and Duration (legend) on Solar Hybrid Net Value



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CAPACITY VALUE

The capacity contribution of a hybrid is less than the sum of its parts

The capacity contribution of hybrid projects varies by region, and depends on configuration and operational constraints. Berkeley Lab developed a simple algorithm for calculating the capacity credit of hybrid plants, suitable for exploratory analysis. Shared hybrid project infrastructure can cut costs but may reduce the capacity value.

Capacity accreditation is critical for hybrids

Power systems require sufficient generating capacity to meet peak electricity demand, often much higher than average demand. Variable renewables can contribute to meeting this need. However, their contribution tapers with increased penetration due to shifting demand patterns, posing a barrier to deep decarbonization. Coupling renewables with storage mitigates this challenge and thus provides a pathway to more-reliable clean power. Market operators and utility planners are defining how hybrid resources contribute toward resource adequacy targets.

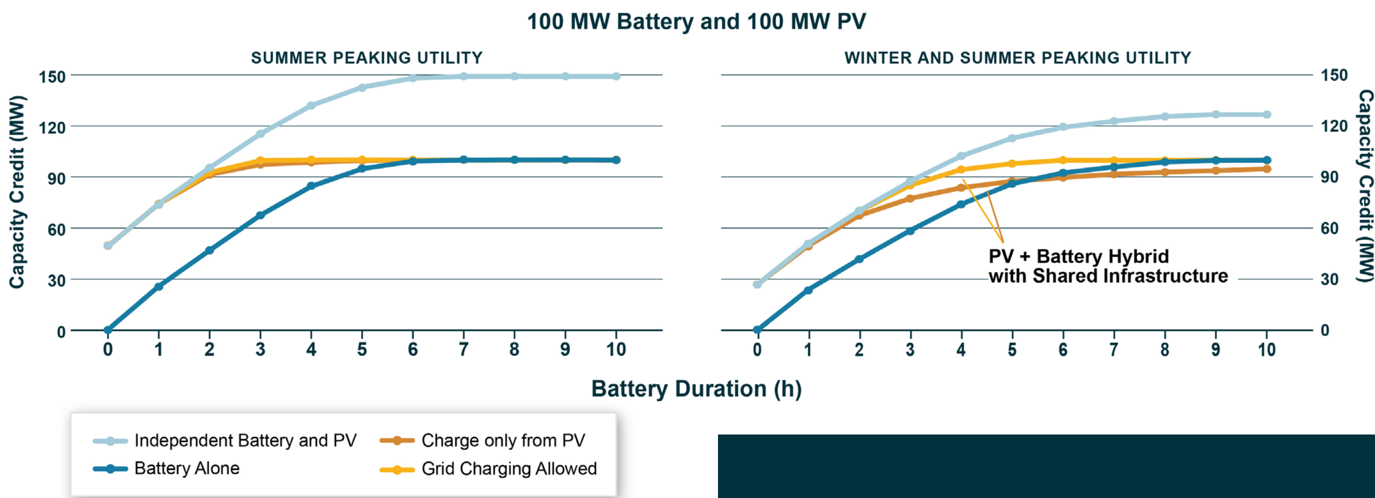
New methods are needed to easily evaluate the relative capacity contributions of hybrids

Widely-trusted methods (e.g., Effective Load Carrying Capability or ELCC) to determine the capacity credit of individual resources rely on data-intensive and complex probabilistic models. With these models, it is difficult to explore changes in capacity contributions across a wide range of configurations, operational constraints, regions, and scenarios. Berkeley Lab developed and validated new approximation methods, which are well-suited to explore how capacity accreditation for hybrids may change in an evolving grid.

The capacity contribution of hybrids is not the sum of its parts

Hybrids often share infrastructure among components or introduce new operational constraints. Shared infrastructure, including inverters or interconnection with the grid, can lead to competition for limited capacity, lowering the hybrid's capacity contribution relative to the sum of the capacity contribution of the hybrid's individual elements. This is most evident when the timing of renewable generation aligns with periods of high reliability risk. Operational constraints, such as charging storage only from the generator, can similarly lower the capacity contribution if periods of high risk occur during low renewable production.

FIGURE 8. Capacity Credit Comparison between Battery, PV, and Hybrid Projects with Varying Storage Durations



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ANCILLARY SERVICES

Ancillary service markets are a valuable yet fleeting option for hybrids

Berkeley Lab analysis shows that hybrid projects can unlock significant value from ancillary service (AS) markets, at least in some regions. But AS markets are thin and can become saturated by battery projects that are currently in interconnection queues. Expecting additional AS revenues to offset declining energy and capacity value may be a risky strategy for wind and solar hybrid project owners.

AS provision can provide additional market opportunities for hybrids

As wind and solar energy supply a larger share of electricity generation, there is growing interest in enabling these resources to provide additional reliability services to the grid through participation in AS markets. This opportunity could provide an extra source of revenue for hybrid project owners to offset the declines in energy and capacity value that result from higher solar and wind penetration. It could also provide system operators with access to low-cost reliability services and a new tool for addressing emerging system constraints.

AS markets offer significant boost in hybrid project revenue

We estimated additional revenues to hybrid solar and wind project owners from participating in AS and energy markets, relative to energy markets alone. We focused on markets for regulation reserves, which typically have the highest prices among AS products. We find that participating in regulation markets can yield additional revenue ranging from \$1 to \$33/MWh (+1-69%) for solar and wind hybrid projects (Figure 9).

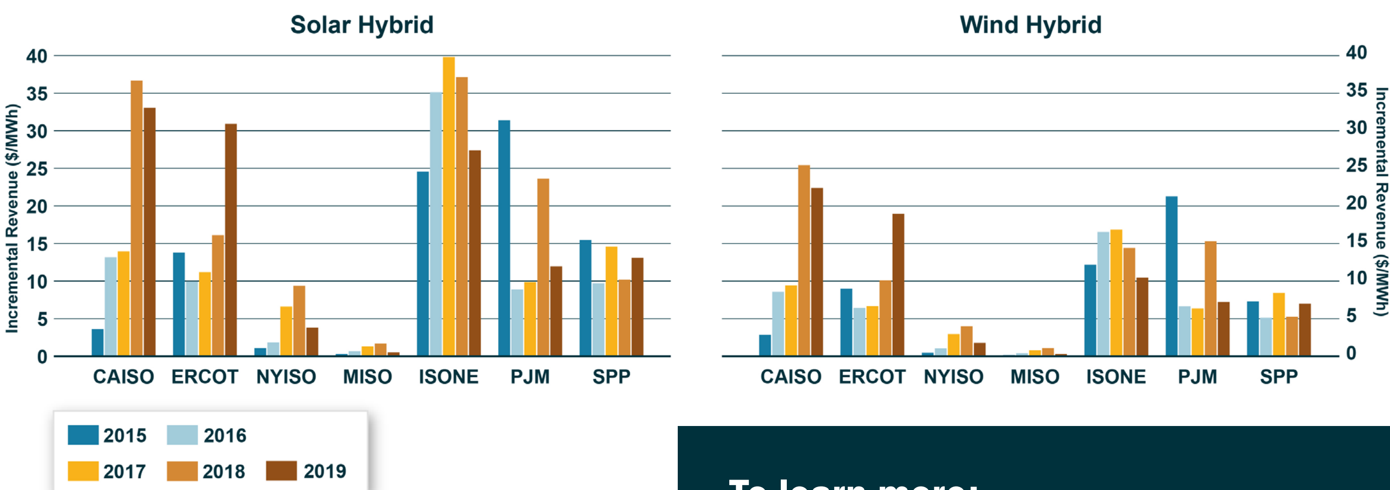
ISO/RTOs could differentiate AS products to prioritize hybrid participation

The distinction between separate upward and downward regulation products can enable more efficient provision of regulation reserves by wind, solar, and storage projects. Independent system operators (ISOs) and regional transmission organizations (RTOs) should first prioritize the participation of hybrid projects in AS markets, and then consider how standalone wind and solar projects can participate.

AS markets, however, are relatively thin

Supply growth can lead to market saturation and AS price decline, even in regions with high incremental value for standalone and hybrid projects. In 2017, ISOs/RTOs procured an average of around 60-800 MW (0.3-0.9% of peak demand) of regulation reserves and 600-2,600 MW (1-4% of peak demand) of spinning reserves. In comparison, ISOs/RTOs had more than 289 GW of standalone and hybrid storage in their interconnection queues at the end of 2021, relative to total regulation and spinning reserve requirements of 4.8 GW and 7.8 GW.

FIGURE 9. Incremental AS Revenue (\$/MWh) to Solar and Wind Hybrid Projects



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MARKET PARTICIPATION

Hybrids can more flexibly engage with electricity markets

The multiple possible configurations of hybrid projects increase the opportunities for and complexity of bidding and dispatching into electricity markets. Developers will be able to evaluate the risks and rewards of operating hybrids as a single unit or as multiple parts with different capabilities. Grid operators may find new ways to tap hybrids to maintain reliability. The Federal Energy Regulatory Commission (FERC) has issued only broad electric storage rulings that are not yet specific to hybrid resources.

Two high-level market participation models are being considered

Hybrid projects could interface with wholesale electricity markets as either a single, fully integrated resource, or separate, but co-located, resources. As an integrated resource, the hybrid project operator has to forecast wind or solar and manage its batteries when developing market bids. Managed as separate resources, the wholesale market operators will implement methods to manage the dispatch of batteries and the variability of the wind or solar while accounting for any coupling constraints.

ISOs/RTOs continue to work on model details

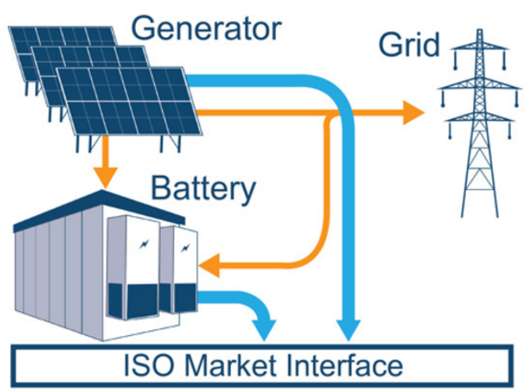
In the absence of a FERC ruling on hybrid participation, grid operators have initiated stakeholder proceedings to develop definitions and business practices related to hybrids. Infograph 2 outlines the market interfaces (blue arrows)—which may include market bids, forecasts, interconnection requirements, and/or operating parameters — which could vary within a model category even while electricity flows ultimately are the same (orange arrows). The Electric Power Research Institute and Berkeley Lab identified a number of challenges for grid operators who will need to know what to expect, as a hybrid project could alternate from being a wholesale seller to a buyer of grid power, depending on market conditions. This could have big implications for resource planning, forecasting, and market power mitigation.

Developer preferences are mixed

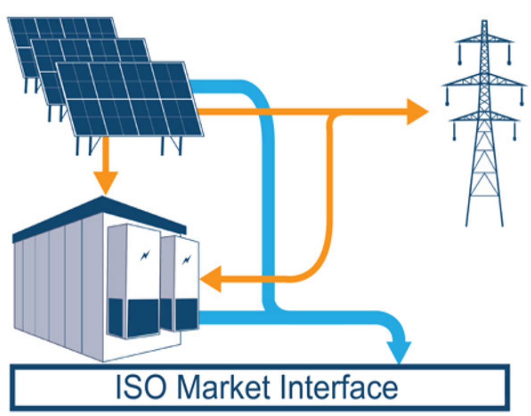
Developers and market operators will evaluate the cost and revenue implications of each model. Currently, the separate but co-located model is the most popular option in California. However, in cases where hybrids aim to follow dispatch signals beyond wholesale market prices (e.g. reducing peak loads, incentive program payments, or resiliency benefits), hybrid project owners may favor the high level of autonomy offered by the fully integrated model. Regulators should try to maintain participation flexibility in order to spur innovation.

INFOGRAPH 2. Spectrum of participation models for hybrid resources

a) Separate independent resources



b) Single, self-managed resource



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OPERATIONS

The power system value of hybrids depends on how they are operated

The operational strategies of a PV+storage hybrid plant are a key driver of its market value, in addition to technical characteristics and location. Berkeley Lab used empirical data to analyze the value impact of different battery dispatch choices. Understanding the prevalent battery charge and discharge signals and aligning related incentive structures with grid needs is increasingly important as the hybrid sector grows.

Not all large-scale PV+storage hybrids focus on wholesale price signals

Models of PV+storage hybrid behavior often assume that project operators optimize battery usage for wholesale market revenue as merchant plants. But studying empirical dispatch data from hybrid plants across the United States, we found that only a minority of projects operating in 2020 focused primarily on the price signals of organized wholesale markets. Instead, participants in special storage incentive programs such as MA SMART focus on the timing of incentive payments (see panel a of the figure), load-serving entities try to reduce their exposure to capacity and transmission demand charges (panel b), and large energy consumers prioritize resiliency and utility bill minimization. These alternative business models can result in higher revenues for the project operators, but do not optimize storage dispatch from a grid perspective (panels c+d), and yield at times only stunted grid benefits ($1-$48/MWh-PV).

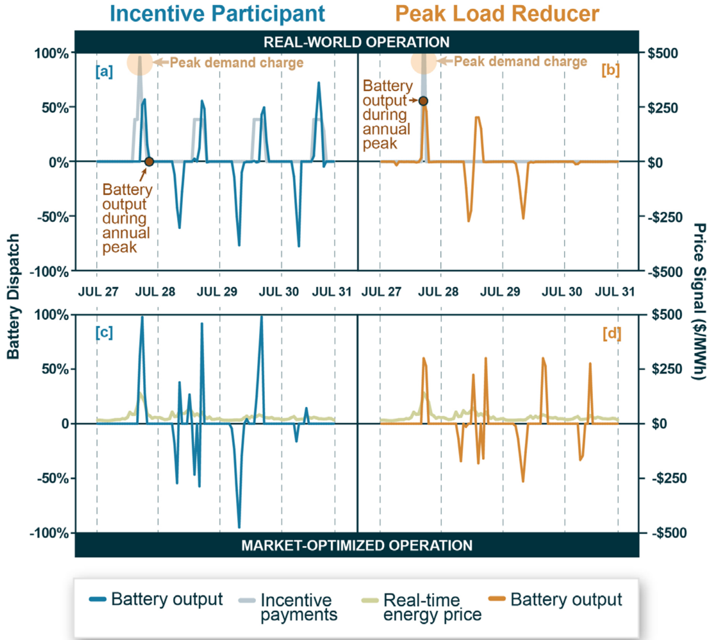
Contractual requirements can restrict the flexibility of PV+storage hybrids, preventing optimal dispatch

A sampling of PPAs for PV+storage hybrid projects finds a number of restrictions often imposed on the battery operation, such as limiting the number of cycles per year (and per day), state-of-charge requirements and depth-of-discharge limitations, or even who controls the dispatch (buyer versus seller, or in some cases shared). Though most of these restrictions stem from battery warranties and efforts to manage degradation, they can nevertheless cause storage dispatch to diverge from what is optimal, based on wholesale power price signals.

Using behind-the-meter storage to maximize solar self-consumption provides little market value

Net billing tariffs, which have become the predominant successor to net-metering, provide reduced compensation for solar generation exported to the grid. This arrangement encourages solar customers to install storage in order to shift solar production to times when it can be self-consumed. For recent historical market prices, we show that operating storage in this manner produces effectively no value to the bulk power system. This compares to a potential annual value of $16-$33 per kWh of storage capacity if operated to optimize its market value. That value gap persists even in higher solar futures, owing to the fact that storage used for solar self-consumption tends to stand largely idle on system peak load days.

Figure 10. Empirical (top) vs. market optimized operation (bottom) and price signals for an incentive participant (left) and peak load reducer (right)



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DISTRIBUTED HYBRIDS

Growth of customer-sited PV+storage hybrids offers new opportunities

Roughly 30% of all U.S. battery storage capacity installed through 2020 was behind-the-meter (BTM), much of that paired with solar PV. Drawing on data collected through its annual Tracking the Sun report, Berkeley Lab characterizes key trends in this budding market.

Storage attachment rates are steadily rising for residential PV, but not so much for non-residential BTM PV

Storage attachment rates for residential PV have been steadily growing, though are still a small share of the market, representing 6% of U.S. residential PV systems installed in 2020 (see Figure 11). In the non-residential market, just 2% of PV systems installed in 2020 included storage, as those customers are more likely to install storage on a standalone basis. Within both the residential and non-residential markets, Hawaii is in a class of its own as a result of net metering reforms that incentivize storage for solar self-consumption. California residential customers may be motivated to add batteries by power shutoffs imposed to prevent wildfire risk, along with state incentives.

Residential PV+storage applications are becoming larger

Most residential PV+battery systems include a single 5 kW battery providing roughly 2 hours of storage. However, as customers have sought greater backup power capabilities, it has become more common to install two or more of such batteries, growing to 40% of all paired residential systems installed in 2020. System configurations within the non-residential market are much more varied, with median storage system sizes of roughly 100 kW / 200 kWh for paired systems installed in 2020.

Residential PV installers have embraced storage more broadly than their non-residential counterparts

Roughly half of all residential PV installers have installed at least one paired PV+battery system, while only 17% of non-residential firms have done so. That said, the residential market remains highly concentrated, with 10 firms representing over 60% of paired residential installs in 2020, and just two firms—Tesla and SunRun—representing 40%. The non-residential market, by comparison, has become less concentrated over time, with no single firm representing more than 10% of paired installs in 2020.

Pricing for paired residential systems has been trending up

Adding storage to BTM PV increases the total installed price by about $1000/kWh of storage, with values ranging from $700-1300/kWh. For a typical residential system, this adds roughly a 30% premium to a standalone PV system. Among residential installers with the greatest number of paired systems, median installed prices and reported storage costs rose in recent years, reflecting supply-chain constraints as demand continues to grow.

Figure 11. Residential and non-residential storage attachment rate

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FUTURE RESEARCH

Where next? Priority areas for hybrid power research

While hybridization of power plants provides opportunities to ease the challenge of balancing intermittent renewable resources, its relative novelty means that research is needed to facilitate integration and promote innovation. Berkeley Lab's ongoing work focuses on themes of hybrid valuation, market rule development, and customer resilience opportunities. The end goal of this research is to support private- and public-sector decision-making related to hybrid power deployment.

More research is needed to understand the full capability of hybrid projects

Evaluating the benefits and limitations of hybrid projects is challenging due to the complexity of combining multiple energy, storage, and/or conversion technologies. Project developers, system operators, planners, and regulators would benefit from better data, methods, and tools to estimate the costs, values, and system impacts of hybrid projects. Hybridization poses new risks and new opportunities to energy systems.

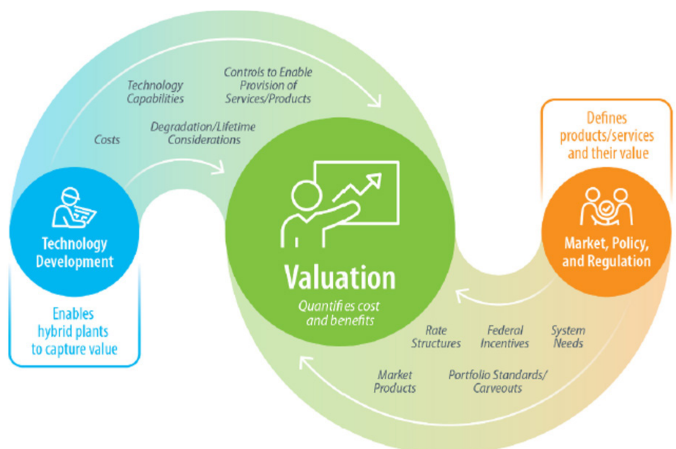
The U.S. Department of Energy (DOE) has identified three high-priority hybrid research topics

A recent DOE report, Hybrid Energy Systems: Opportunities for Coordinated Research, identified near-term opportunity areas for research and development on hybrid power projects (Infograph 3): Technology development can develop and demonstrate new hardware and software that enables co-optimization of hybrid resources. Markets, policy, and regulation research can develop frameworks to ensure efficient investment in and operation of hybrid projects. Both research areas support refined valuation methods that quantify hybrid project cost and benefits in the electricity system.

Berkeley Lab's ongoing research focuses on "valuation" and "market, policy, and regulation" topics

We will examine how market designs impact hybrid project dispatch, system reliability, and overall economic efficiency in future power systems and investigate how hybrid configurations may vary in response to transmission congestion. We plan to assess the capability for behind-the-meter PV+storage to provide back-up power to end-users of electricity during long and short-duration power outages. In addition to targeted analyses, we will continue to track and study hybrid deployment trends.

INFOGRAPH 3. Summary of Priority Areas for Research on Hybrids and their Mutual Dependencies



To learn more:

See the **U.S. Department of Energy report**
Sign up for our **email list**
or contact Will Gorman: **wgorman@lbl.gov**
and Jo Seel: **jseel@lbl.gov**

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